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(54) Digital movement controller for automatic multi-axis machines

(57) In a multi-axis machine tool, welder, sprayer, or robot, the spatial position of the machine depends upon the contemporaneous positions of its several axes. Each axis (8 to 13) is moved by an actuator and its movement is monitored by a transducer electrically connected to an individual control module including digital data processing means that repeatedly determines the distance through which the axis has moved, compares the position of the axis with an interim target position and supplies a control signal to the actuator to cause it to move to a required direction and velocity during the next time period until the axis has reached its final target position. A central controller supplies target positions to the several control modules through a common data highway to bring about required axis movements.

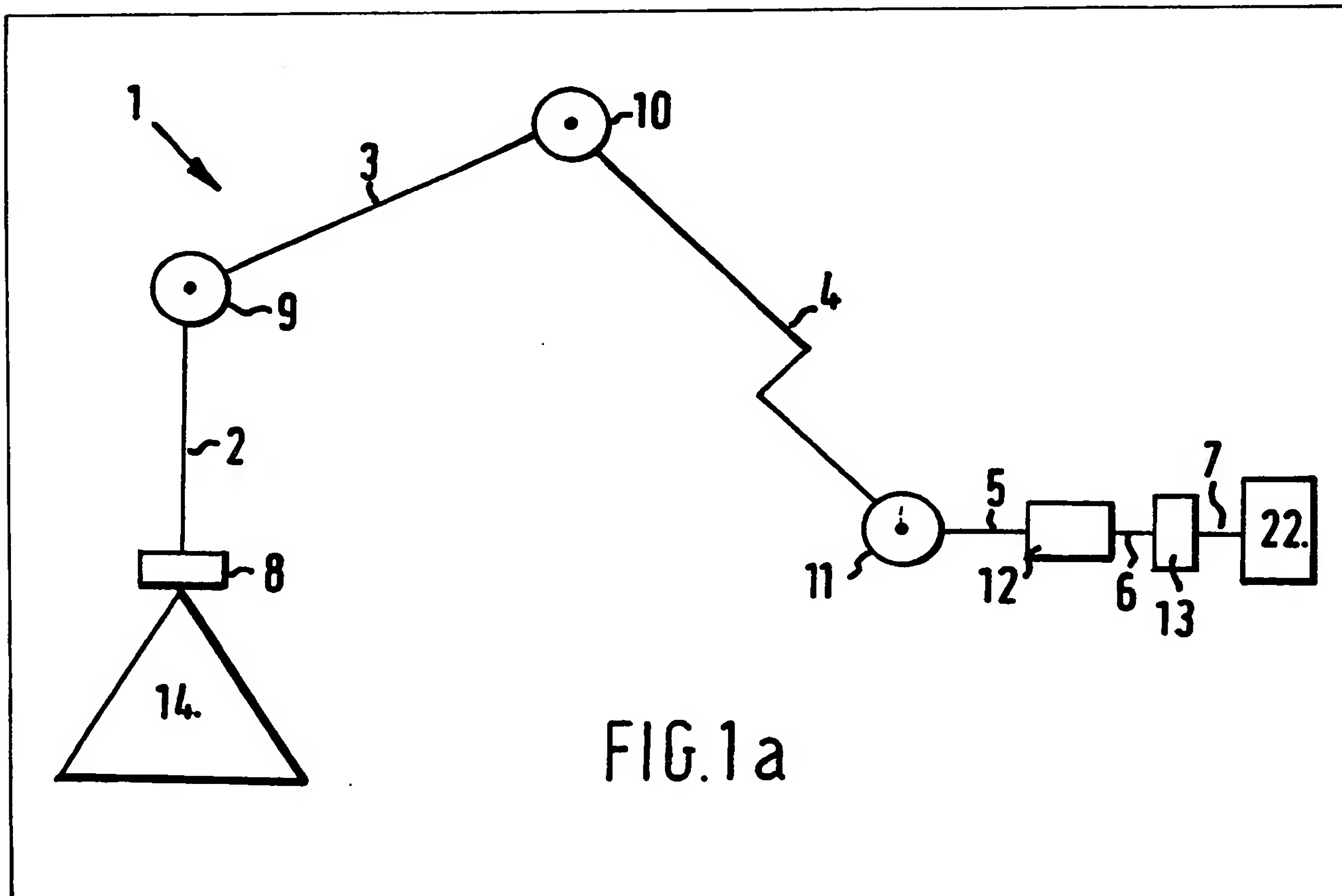

FIG.1a

GB 2 102 590 A

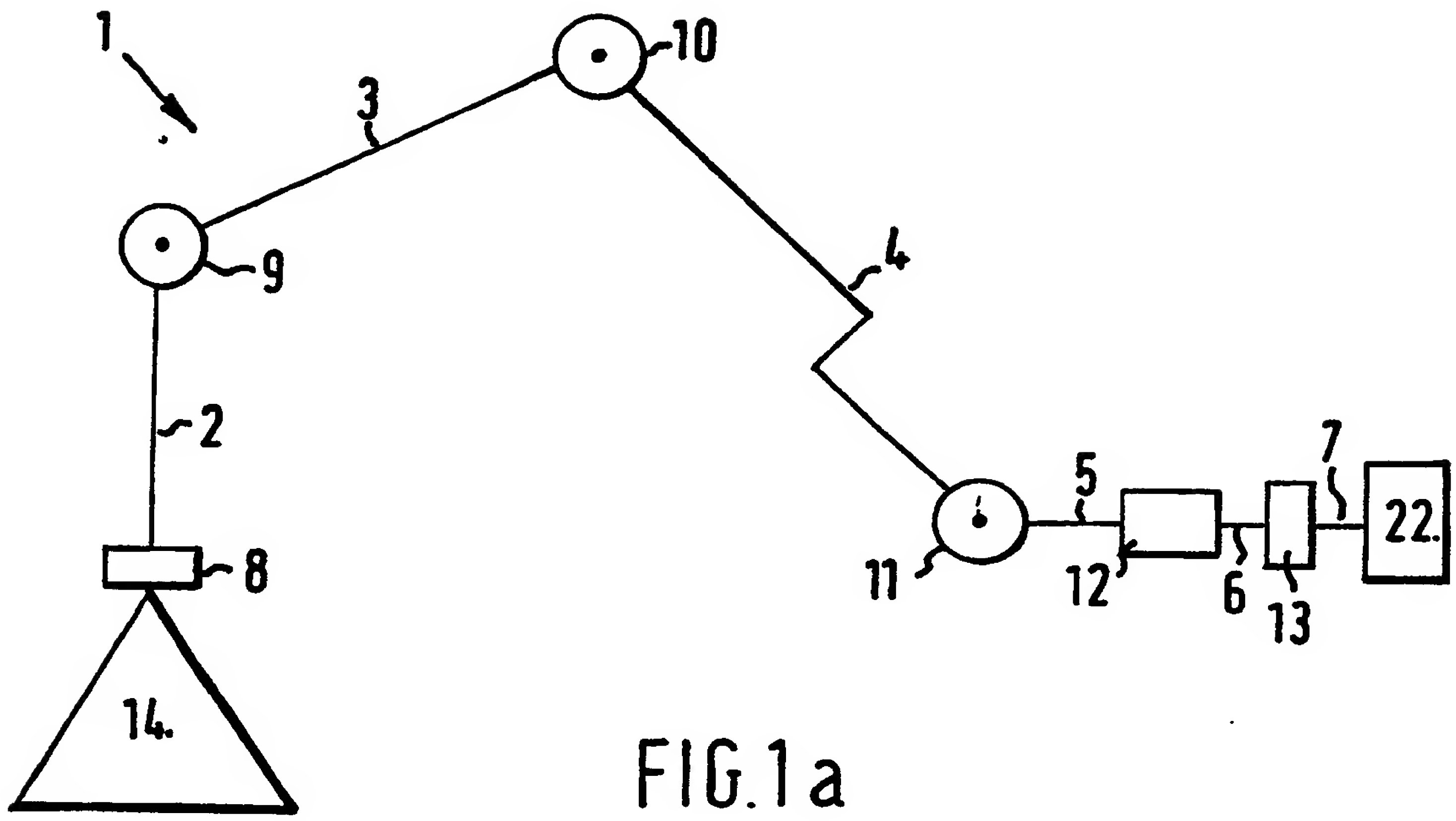

FIG.1a

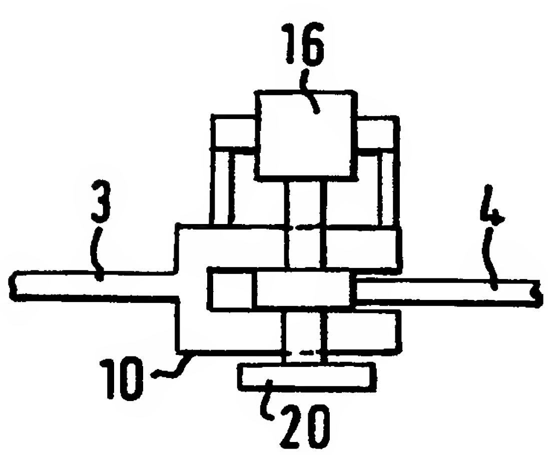

FIG.1b

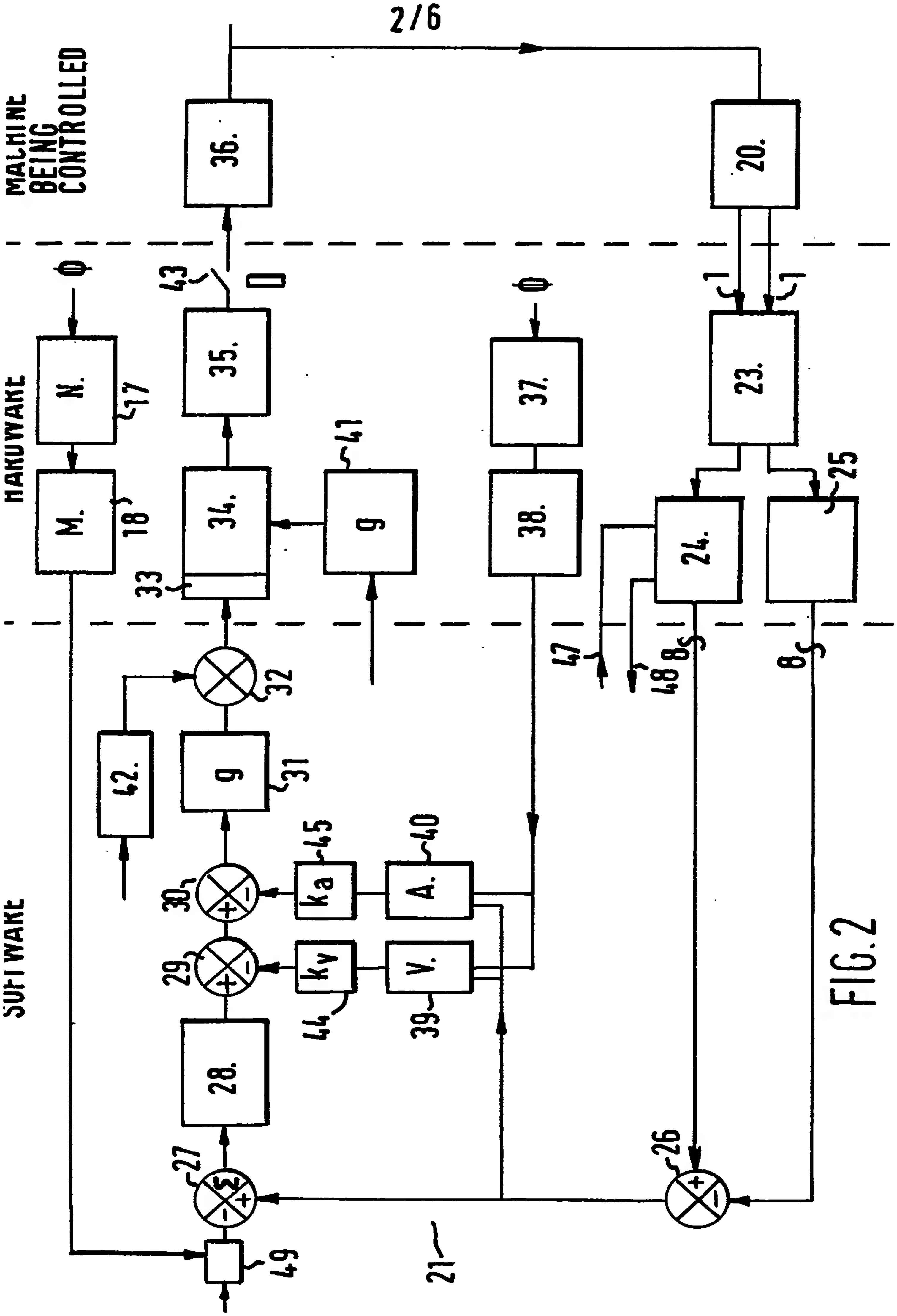
MACHINE BEING CONTROLLED
HARDWARE
SOFTWARE
36.
20.
35.
37.
23.
N.
M.
34.
g
38.
24.
42.
g
ka
A.
kv
V.
28.
49
21
26
27
29
30
31
32
33
39
40
41
43
44
45
47
48
8s
8s
17
18
25
1
1

FIG. 2

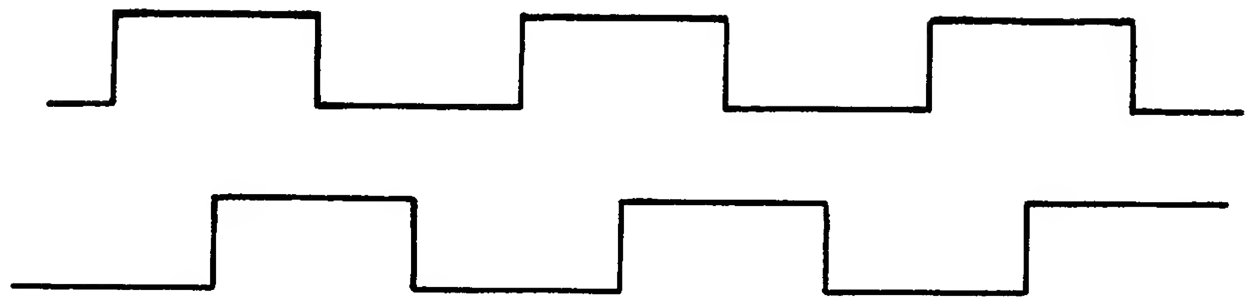

FIG.3a

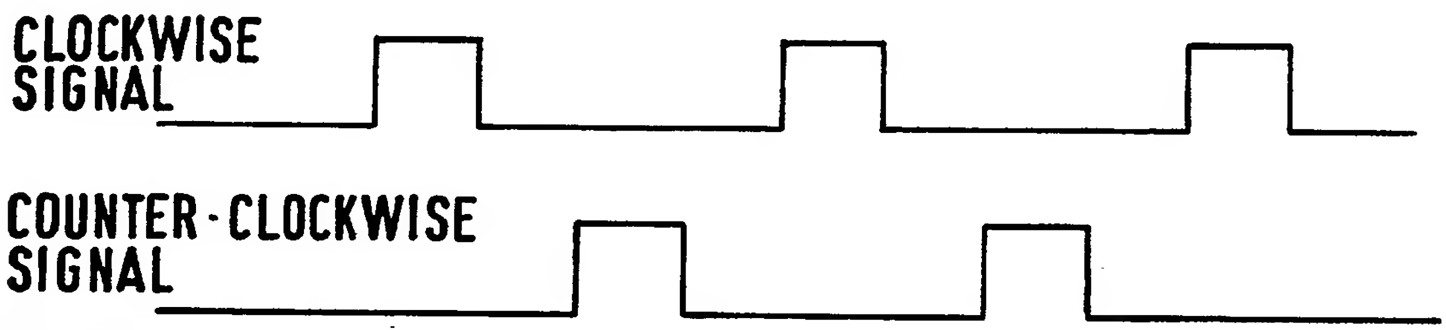

FIG.3b

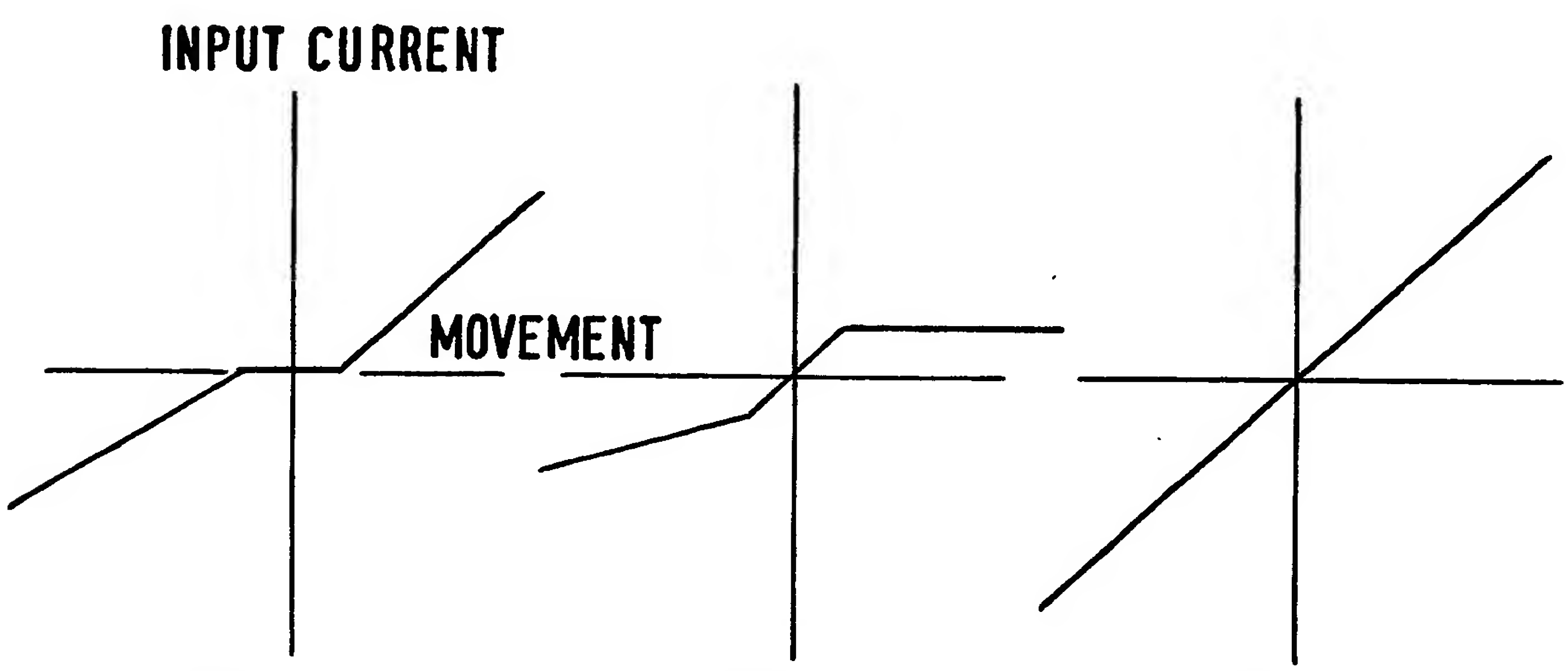

FIG.4a FIG.4b FIG.4c

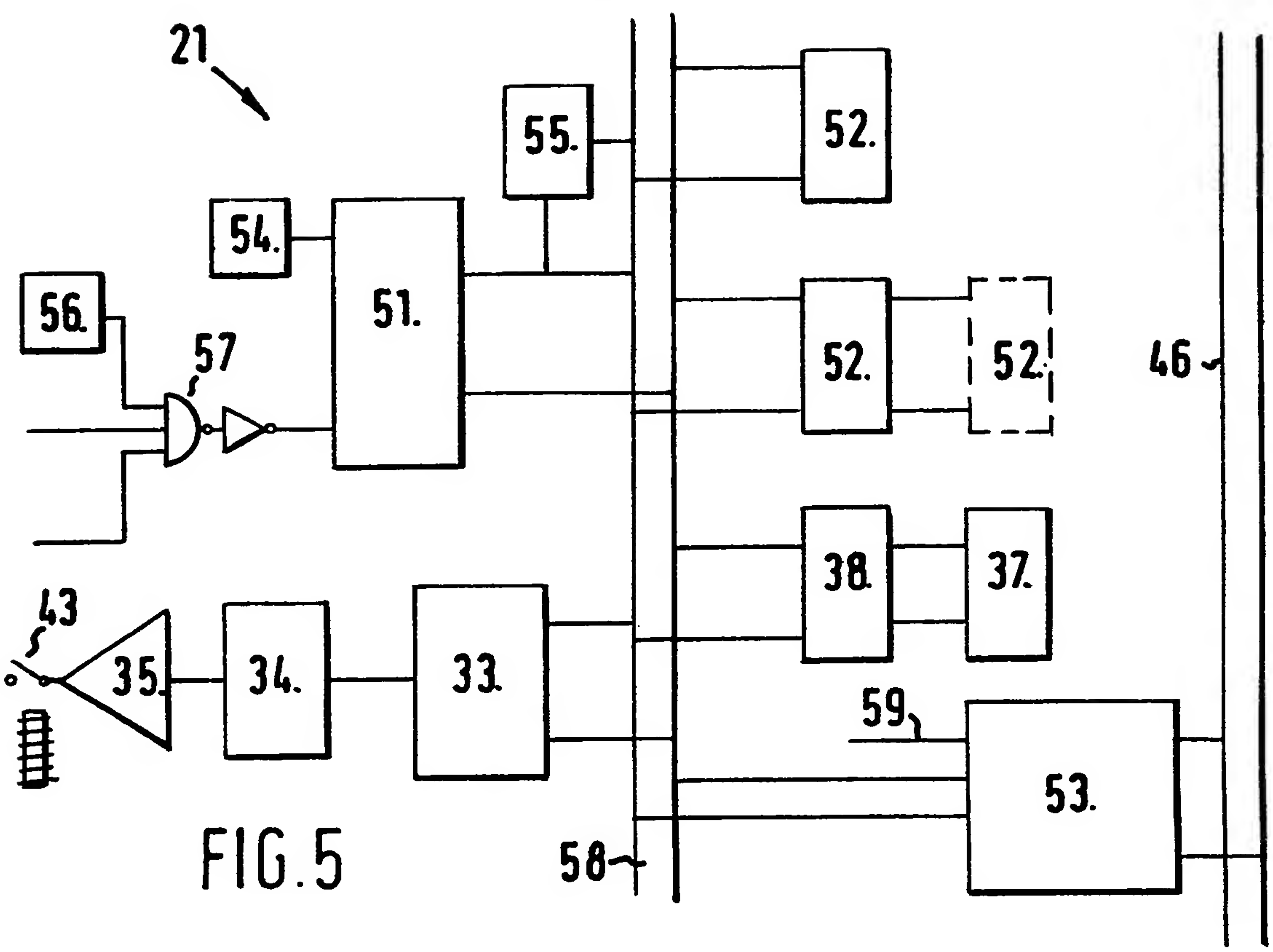

FIG.5

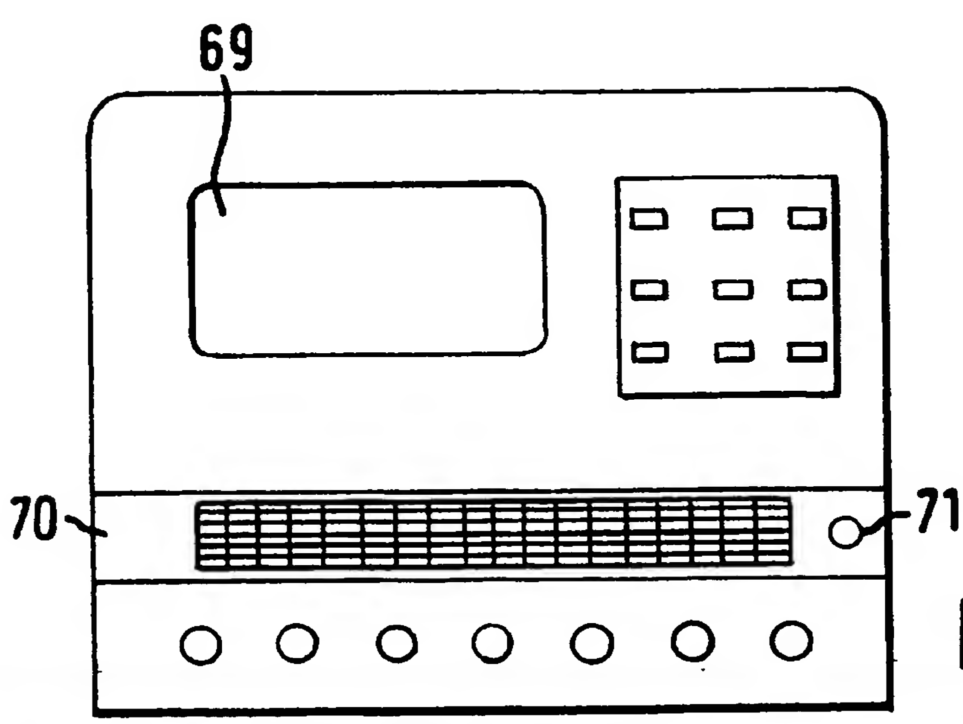

FIG.8

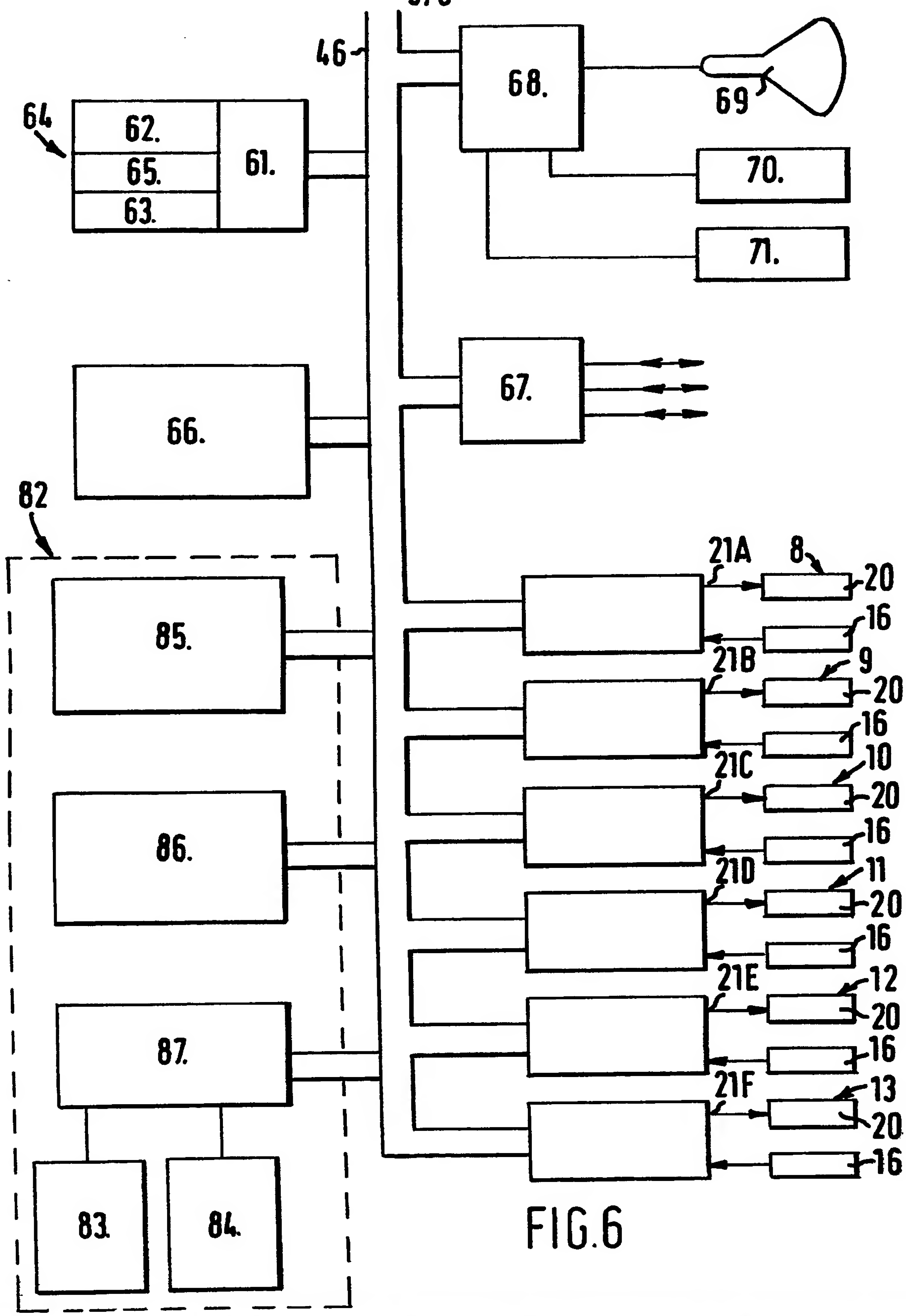
46
64
62.
65.
63.
61.
68.
69
70.
71.
67.
66.
82
85.
86.
87.
83.
84.
21A
8
20
16
21B
9
20
16
21C
10
20
16
21D
11
20
16
21E
12
20
16
21F
13
20
16

FIG.6

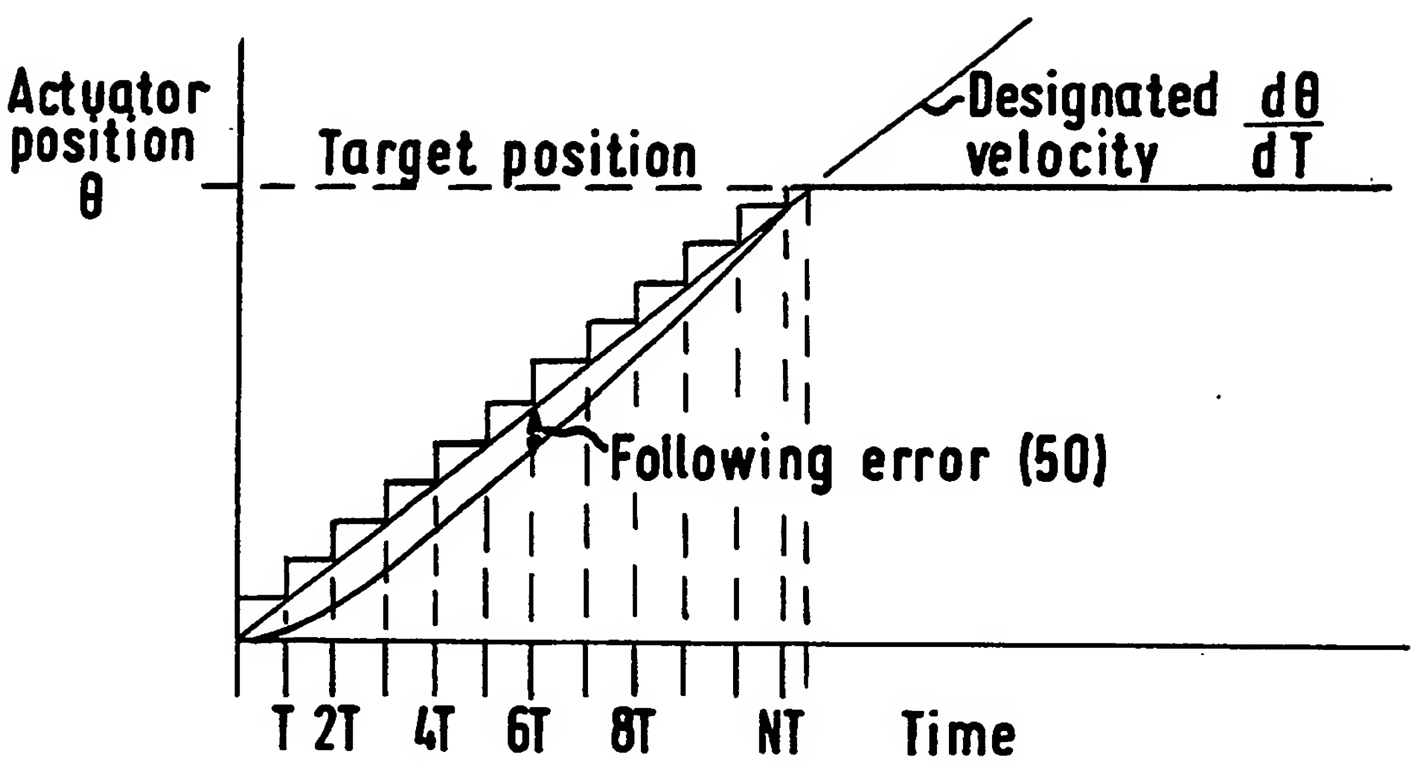
Actuator position θ
Target position
Designated velocity dθ/dT
Following error (50)
T 2T 4T 6T 8T NT
Time

FIG.7

SPECIFICATION

A digital movement controller for automatic multi-axis machines

This invention relates to electronic circuits for the control of Robots and other automatic machines for the manipulation or machining of industrial components.

It is well known to control automatic machines by linear or analogue electronic circuits and these have traditionally had the advantage over digital circuits when applied in closed control loops, of giving adequately fast response times to handle the resonant frequencies, typically of up to 10 cycles per second, of the mechanisms controlled.

Digital circuits, however, offer the advantage of greater mathematical precision, and when such digital circuits are controlled by processors using stored programs, the further advantage of versatility is obtained.

The present invention combines the use of analogue techniques in the final drive circuits to the actuators of the controlled mechanism, with the mathematical precision of digital circuits and the versatility attainable with microprocessors without sacrificing speed of response.

More particularly the invention provides a control system for a multi-axis machine tool, welder, sprayer, robot or like mechanism in which the spatial position of the machine as a whole depends upon the contemporaneous positions of its several axes, wherein each axis is moved by an actuator and its movement is monitored by a transducer electrically connected to an individual control module including digital data processing means that repeatedly determines distance through which the axis has moved, compares the position of the axis with an interim target position and supplies a control signal to the actuator to cause it to move in a required direction and velocity during the next time period until the axis has reached its final target position and a central controller that supplies target positions to the several control modules through a common data highway to bring about required axis movements.

Hitherto, when using processors, economic considerations have dictated that the several axes of a multi-axis mechanism should share the services of a single processor(for example a minicomputer), but with complex multi-axis mechanisms that time-sharing introduces significant speed penalties.

Now that microprocessors are becoming more plentiful and of more modest cost, it has become feasible to use separate microprocessors to control each of the several interdependent axes and an additional common control microprocessor to coordinate the operation of the several axis controllers.

By this means, an adequate speed of response (typically 30 millisec.) can be ensured and sufficient spare processing capacity is available to facilitate the incorporation of further refinements only previously available in extremely complex and expensive systems.

The flexibility resulting from the use of a microprocessor in the control of each actuator makes it possible to design a standard printed circuit module which can be adapted by the provision of appropriate software, to match the required drive characteristics of a wide variety of integrating actuator mechanisms using hydraulic, pneumatic or d.c. motor drives.

While the immediate control of each actuator is effected by one dedicated printed circuit module, in a closed loop mode, depending on the feedback of positional data from an optical transducer associated with the controlled actuator, the overall control of the system and co-ordination of the movements of each individual actuator to produce a required overall movement of a workpiece or machine head, is vested in an additional controller module which itself comprises another printed circuit board equipped with its own microprocessor and associated memory circuits. Like the modules controlling individual actuators, the Controller module has high adaptable characteristics, so that the same assembly of Controller plus actuator control modules can be used to control a variety of automatic machines such as welders, robot handling devices, paint sprayers or machine tools.

To further facilitate the interfacing of the control system with a variety of existing and future machines and overall Production line control systems, the present system makes use of printed circuit boards, interconnections and power voltages consistent with current international standard recommendations.

To facilitate the initial setting up of machines, the definition of the required control parameters and for optional manual control, the system is provided with a comprehensive control panel comprising a cathode ray tube display, a series of programmable control keys and appropriate manual controls.

The number of actuators to be controlled is flexible, the basic cabinet provided having capacity to accommodate ten actuator control modules together with one Controller, the circuits associated with the control panel and the necessary power supplies. In a preferred application the system is used to control six actuators in a robotic work-handling device, the six axes in which the actuators operate being X, Y and Z with respect to a designated datum point, and "pitch", "roll" and "yaw" of the workpiece with respect to a designated angular orientation.

The invention will be understood from the following detailed description with reference to the accompanying drawings wherein:

Fig 1a illustrates the construction of a typical robotic arm, having six "joints" each controlled by actuators, and each having an optical transducer to feed back electronic signals to the controller and Fig 1b shows the construction of a typical joint;

Fig 2 represents in block schematic form, the fuctions provided by one of several identical axis control modules;

The drawing(s) originally filed were informal and the print here reproduced is taken from a later filed formal copy.

Fig 3 illustrates the input pulses supplied from an optical encoder to an axis control module, and the pulses employed in the module after pre-processing;

Fig 4a illustrates a typical transfer function for an actuator,

Fig 4b shows a correction function which may be applied in the axis control module to produce an ideal effective transfer function shown in Fig 4c;

Fig 5 represents in block schematic form the hardware units included in the axis control module, and their interconnections;

Fig 6 shows in block schematic form, the complete control system hardware, including the optional maintenance module;

Fig 7 illustrates actuator position as a function of time and shows the correction of following error; and

Fig 8 illustrates the physical appearance of a preferred main control console forming the front panel of the cabinet housing the system hardware.

Figs 1a and 1b illustrate in diagrammatic form the structure of a robotic work-handling arm (1) which comprises six independent sections (2-7) interconnected by joints (8-13) each of which is actuated in a rotary movement by a hydraulic actuator (16), while the resulting movement at each joint is monitored by an optical transducer, one of which (20) is shown coupled to actuator (16) in Fig 1b.

It will be appreciated that the effect of a given increment of angular movement at any one joint (8-13) will depend on the contemporaneous setting of all the other joints in the system. The analysis of the motion of any given actuator and its effect on the position of the workpiece is therefore dependent on the position and movement of all the other actuators in the system. It is therefore desirable that the movement of each actuator be coordinated by a common controller module in which a microprocessor modules the behaviour of the entire structure and instructs individual modules (21) (referred to as axis control modules) for the several axes of joints (8-13) what increment of movement its actuator is required to execute next. The axis control module, which has already been loaded with all the necessary data to enable it to interpret the received instructions and to convert these into relevant instructions to the actuator, takes into account all the idiosyncrasies of the actuator to which it is connected, which may include oscillations, deformations under load, non-linear characteristics etc. and which are discussed in more detail below.

The absolute position and orientation of the workpiece (22) is calculated by the microprocessor in the controller module from the data fed to it by individual axis control modules (21A-21F Fig 6) as movements are monitored in each joint (8-13). These movements are continuously monitored with the aid of the optical transducers (20) which in the machine used to illustrate the invention, feed back to the axis control modules a pair of pulses for each increment of angle by which the joint moves. For the sake of this explanation it will be assumed that a resolution of 1 minute of arc is provided and that a pair of pulses are output for each increment of angular movement of this magnitude.

A type of optical transducer used in this kind of application outputs a pair of pulses shifted out of phase with each other by 25% of the repetition rate for each of them. In other words, as the actuator turns in a clockwise direction, one pulse train leads the other by 90°, and when the actuator turns counterclockwise, the second pulse train leads the first by 90° in phase. This arrangement enables the associated electronics to distinguish between clockwise and anticlockwise motion of the actuator. These waveforms are illustrated in Fig 3a for clockwise rotation of the encoder.

The two trains of pulses described above are shown passing from the optical transducer (20) to the Axis control module (21) in Fig 2, where they are interfaced to a CMOS directional logic circuit (23). This logic circuit generates two output pulse streams as illustrated in Fig 3b, one for clockwise movement and the other for counterclockwise movement. The clockwise output from the directional logic circuit is applied to the clock input of a Counter/timer circuit (24) preferably of the type Z80CTC supplied as part of the Z80 microprocessor family of integrated circuits. This counter counts up to 255 and produces a corresponding 8-bit binary output before the most significant bit overflows and the counter reads zero on the 256th. pulse thus counting in modulo 256 without the need of a reset pulse. Similarly, the counter-clockwise output from the directional logic circuit is fed to an identical Counter/timer circuit (25) which therefore counts the counter-clockwise pulses. The directional logic circuit (23) has a multiplying effect and generates via monostable a well defined pulse on both positive and negative going edges of both its outputs.

This increases the precision of the encoder feedback by a factor of four. However, to synchronise closed loop operation an interrupt request pulse is only generated on the positive going edge of the clockwise signals and output on signal line (48) by the directional logic circuit. In addition, this interrupt request can be enabled or disabled within the axis controller by a signal on input line (47) so that interrupts can be prevented until the end of a calculation activity.

Typically this interrupt is enabled after 3ms, since this is the duration of the loop closure calculation process. During this time, if the actuator is moving, a change in the accumulated count will have taken place, but the counter (24) will wait for the next positive going transition of the clockwise phase before responding to the enable pulse (47) by outputting the interrupt request pulse (48). If the actuator is moving slowly, the change in the accumulated count within about 3ms may be as little as 4 clockwise pulses. If the actuator is moving fast, there will be many pulses accumulated in 3ms (in multiples of 4), but the number will always be much smaller than 256, therefore there can be no ambiguity in the magnitude of the accumulated count.

The 8-bit binary counts from counter (24) and counter (25) are passed to the microprocessor where the counterclockwise count is subtracted (26) from the clockwise count to produce a signed count of the

net change in angular position of the actuator as sensed and signalled by the optical transducer (20).

One Megahertz clock pulses (ø), derived from a crystal oscillator are divided down by a preset factor N and by an additional fixed factor M in two cascaded Counter/timer circuits (17 and 18) type Z80CTC to produce a series of timed Interrupt-Enable pulses at equal predetermined intervals T, where T = MxN microsec.

These pulses are shown along the time axis of a graph relating actuator position θ and time in Figure 7.

The target position for the actuator (36) at the end of the forthcoming move and the planned angular velocity to reach that position, both expressed in the form of 16-bit binary numbers, are loaded into the buffer memory (53) shown, in Figure 5, by the central control processor (61) shown in Figure 6.

When the Axis Control Module is ready to act on the instructions in the buffer memory (53) its microprocessor (51) shown in Figure 5 reads out the intended angular velocity from the memory and calcalculates the cumulative angular distances from the prearranged datum, to which the actuator should have moved at each of the times of the successive Interrupt Enable pulses. The actual positions reached by the actuator as defined by the signed count output from stage (26) as described above, at the moment of each interrupt pulse (output from unit (24) on signal line (48) are compared in stage (27) with the successive intermediate target figures for the current and the next interrupt to calculate the error to date and the distance to be covered in the next time interval T. This determines the velocity required to reach the correct position by the next interrupt. This procedure is repeated until the calculated position for the next interrupt is beyond the final target position, when the final target position is substituted in the calculation for the normally calculated position.

This count is compared in stage (27) with the output from stage (26) and also accumulated in stage (27) to give a signal denoting the cumulative error to date in the position of the actuator as compared with its intended position.

Disregarding for the present, the calculations carried out at stages (28, 29, 30, 31 and 32) the output from stage (27) is passed to a Parallel Input/Output Device (33) which is preferably the Z80PIO integrated circuit forming part of the Z80 microprocessor set of circuits. This device forms an appropriate interface from the Z80 processor to a Digital to Analogue converter (34). The analogue voltage output from this converter is fed to an output amplifier module (35) wholse output current is proportional to the input voltage supplied to the amplifier from the D/A converter (34), except in so far as an optional modification has been built into module (35) to compensate for any non-linear characteristics of the actuator (16) which is driven by the output current from the amplifier (35). The movement of this actuator continues in subsequent intervals between interrupts, until the destination co-ordinates of the workpiece have been reached, and the optical transducer (20) continues to monitor the movement of the actuator (36) throughout the process.

A pair of cascaded counter/timers (37,38) similar to those (14,15) alreay mentioned, are also clocked by the crystal oscillator to give a further time reference. This time reference is used in two further calculations by the microprocessor. The signed feedback change output from calculation stage (26) is input together with the time reference from timer (38) to calculation stages (39) and (40). In stage (39) the angle increment is divided by the time increment to calculate the angular velocity, while in stage (40) the angular velocity is further divided by the time increment to calculate the prevailing angular acceleration.

The prevailing velocity calculated in stage (39) is multiplied by a scaling factor "k_v" which has the dimensions of time to produce an output with the same dimensions (increments of angle) as the output from stage (27). These last two mentioned quantities are input to calculation stage (29) to derive a difference, whose effect is equivalent to that of negative velocity feedback in an electronic hardware circuit, and therefore has a stabilising effect cancelling out any tendency to oscillate on the part of the closed loop circuit. Such tendency would be most likely to occur as a result of mechanical resonances in the actuator mechanism.

Factor "k_v" is adjusted to an optimum value to minimise any such oscillation. The acceleration output parameter from calculation stage (40) is similarly applied to the output from calculation stage (29) in calculation stage (30), in order to apply a similar negative feedback stabilisation against any possible second order oscillation effects which might remain after the first stage of negative feedback had been implemented in stage (29).

Four other optional adjustments will also be explained at this stage, three of which may conveniently be implemented in software and the fourth in hardware. Stage (28) is provided to enable offset errors to be corrected. This type of error results from physical distortion of the mechanical components of the system when subjected to heavy loads, or more probably in a hydraulic system, results when the control circuits having correctly deduced that a certain rate of pumping oil into the hydraulic actuators is called for to produce the remaining movement necessary to take up the intended position, does not know that the weight of the workpiece being lifted is presenting so much resistance to the flow of oil into the pump that the actuator is unable to respond as expected. The offset error correction stage (28) has been introduced to provide for the introduction of a further step function of lift to compensate for this "sagging" effect produced by a heavy workpiece. The magnitude of the correction to be made is measured when the workpiece is stationary.

Stage (31) provides for the input of a non-linear gain factor to compensate for the non-linear transfer function frequently encountered in the operation of hydraulic and pneumatic actuators. If, for example, there is a dead spot near the unactivated position of the actuator, and if the sensitivity for forward motion is different from that of backward motion, as is often the case, a typical transfer function for an actuator

may be as in Fig 4a in which input current is plotted against movement. If then the adaptive gain applied at stage (31) has the form shown in Fig 4b, the combined effect of these two factors will result in the linear overall transfer function shown in Fig 4c, with a correspondingly better dynamic performance.

Stage (32) is provided to enable a controlled oscillation or "dither" to be introduced into the control loop. It is well known that a small amplitude vibration applied to a mechanical mechanism will minimise the effects of static friction by substituting dynamic friction, which is generally lower by a significant factor. Instead of introducing this as a physical vibration, the same effect can be achieved by introducing a controlled "dither" at a suitable frequency and amplitude into the control loop. It has been found, in the preferred embodiment, that a square-wave signal at a frequency of 80Hz introduced into the digital count output from stage (31) at stage (32) and before application to the parallel input/output stage (33) is effective. The 80Hz frequency is conveniently derived by counting down from the basic clock frequency in another counter/timer circuit (not shown in Fig 2) and its amplitude is defined in stage (42).

The adaptive gain control software module (31) may involve a fairly complex calculation, and under certain conditions the time taken for this calculation could limit the speed of response of the rest of the control loop. For conditions when this might be of critical importance, an option is available whereby this function is provided in hardware as shown in Fig 2 at hardware module (41). This would perform the same function as has already been described above for software module (31), but much more rapidly.

A relay (43) is used as a breaker in the circuit between the current amplifier (35) and the actuator (36). This ensures that the control loop can be broken in a fail safe fashion in the event of a power failure or any other circumstances calling for an "Emergency Stop". Interruption of the actuator drive by this means causes the mechanism to stop moving and to remain in its current position until the drive circuit is restored.

The output from amplifier (35) is a d.c. current nominally proportional to the analogue input to the amplifier. This is one form of drive required by integrating hydraulic actuators connected to electrically controlled valves which produce a response proportional to the output current. For d.c. motor applications where it is required to produce a voltage output, this is readily arranged by applying the output current to a load resistor, or by other means.

The error offset correction applied in stage (28) comes into operation only when the workpiece is stationary at the end of a programmed movement. It is only appropriate to apply it after the more conventional effects of time-lag in the attainment of the final position have been accounted for.

By synchronising the interrupt requests from counter (24) to one edge only of the clockwise output pulses, a high precision in the timing of the interrupt is achieved, which is reflected in the accuracy of the time intervals to 1 microsec. in 3 milliseconds, or for longer time intervals, the limit is set by the 1 part 65,000 count limit of the timing counters. In addition the accuracy of position resolution can be increased when required by means of an optional alternative mode for synchronising the interrupt requests to any of the four pulse edges of the outputs from counters (24,25). By this means it is possible to improve the angular resolution available by a factor of four. This is greater than is normally required. It can be implemented by means of a keyboard command on the control panel (70), and is normally only used when setting the initial datum positions for a machine.

It is found that the calculated velocity and acceleration signals through the stages (39 & 40) can be subject to random fluctuations, and therefore it is found expedient to provide these stages with digital filtering algorithms in which successive smoothed values of velocity and acceleration (v_{ns}, A_{ns}) are derived from the previous smoothed values ($v_{(n-1)s}$, $A_{(n-1)s}$, by simple calculations of the form:

$$v_{ns} = \frac{K \cdot V_{(n-1)s} + V_n}{K+1}$$

$$A_{ns} = \frac{K \cdot A_{(n-1)s} + A_n}{K+1}$$

where V_n,A_n are the current raw inputs, and V_{ns},A_{ns} the corresponding smoothed values. The factor K may be set as required to give an optimum time constant. A preferred value of K is 3.

The loop gains k_v and k_a in stages (44) and (45) can also be set up by keyboard instructions. It is also possible to disable, i.e. open, these loops from the keyboard when required.

The complete hardware content of an Axis control module (21) is shown schematically in Fig 5, including the Z80 microprocessor (51) and its supporting memory modules (52).

The interface logic and RAM module (53) provides 256 bytes of storage, part of which is used as a buffer between the Axis Control module and the central controller.

Forty eight bytes of data arranged in three blocks of 16, are used to communicate control parameters from the controller to the axis control module and for the interchange of target actuator positions (from Controller to Axis module) and of monitored actual movement towards those positions (from Axis Module to Controller). The actual allocation of the bytes within the three blocks for a typical application is illustrated in Table 1. When the actuator controlled by an Axis Control Module has reached the final target position, it signals to the central Controller with an interrupt.

At any time during the progress of the actuator towards its final position, the controller has access to the buffer (53) and can compare the actual position reached at the last interrupt with the intended position, and can compute the following error (50). Subsequent instructions to the axis Control Module may be modified to correct this error.

Communication between the central controller and the Axis Control Modules is over an Industry standard 86-conductor communication highway (46) as shown in Figure 5. The several Axis Control Mod-

ules (21) all share common signalling lines, their interface buffers (53) being loaded from and interrogated by the Central Controller on a priority interrupt basis.

One of the inputs available on the Z80 microprocessor is a non-maskable input. This is used to initiate a non-maskable shut-down routine. Three inputs are provided to the NAND gate (57), allowing an internal POWER FAIL logic level, a POWER FAIL signal directly from the Power Supply, (56) or a signal from the EMERGENCY STOP button (71) to be used.

The timing signals to the Z80 processor are provided by a conventional clock pulse generator module (54). Internal communication between the units comprising the Axis Control Module is over an internal Z80 data bus (58).

Interrupts to the Interface logic (53) may be initiated either over the external multibus highway (46) or from the Axis Control board itself on input line (59).

Fig 6 illustrates in block schematic form the complete system according to the invention, including six axis-control modules (21A – 21F) all of which are identical and, as described above, are used to drive six actuators (8-13).

The central processor (61) used in the controller is a type 8080 microprocessor. It is assembled on a printed circuit board (64), together with an Arithmetic unit (62) and the PROM and RAM memory units (63,65) intimately concerned with its basic operation. One of the principal operations carried out by the Arithmetic unit (62) is a conversion from cartesian to polar co-ordinates as required to instruct the axis control modules (21) what angular movements are needed from their respective actuators to implement the required movement of the workpiece in three cartesian dimensions. The Arithmetic unit consists of a microprocessor chip with an efficient performance in the cartesian to polar transformation. In particular it is capable of calculating trigonometric functions vary rapidly and accurately.

The optimum movement of the workpiece between its initial and final positions is usually in a straight line and therefore, when the system is programmed in cartesian mode, the algorithms used are those which best meet this criterion.

When it is opportune, or necessary to instruct the machine to move the workpiece via a complex route, for example to avoid an obstruction, manual programming can be used, teaching the necessary program to the machine step my step from the keyboard.

The central processor (61) communicates over highway (46) with a memory module (66) and with an input/output module (67).

The input/output module (67) provides for optically isolated data communication with external modules such as relays, contactors, etc. on other machines with which the operation of the robot must be interlocked.

The CMOS RAM memory card (66) is provided with its own small rechargeable battery wired onto the card to enable data to remain stored therein when the power supply to the rest of the system has been switched off. Due to the low power consumption of CMOS RAM devices, data can be retained in this memory for one month without the battery being recharged.

A further module sharing access to the common highway (46) is the control module (68) for a Visual Display (69), and keyboard (70). Some of the controls on the keyboard may be extended for remote operation by an appropriate Remote Control Unit (71).

The touch-sensitive keys on the main program keyboard (70) may be programmed to meet the requirements of any particular application, being similar in format to the keyboard of a conventional visual display terminal. A typical layout of this keyboard is shown in Fig 8. The Cathode Ray Tube (69) may be used to display alphanumeric data input from this keyboard, or tabulated data derived from the axis modules or the central controller.

The predetermined control software for the system is provided in PROM form, and the variable parameters entered from the keyboard are held in the battery backed RAM modules (66). When it is necessary to generate a new program, or when diagnostic routines are called for, a special maintenance module (82) can be plugged into the system. This module includes a floppy disc driver (83), an additional visual display (84), a dynamic RAM module (85) and a PROM programmer (86).

Maintenance routines, or any other development software, may be stored on floppy discs and loaded via the disc drive module (83) to the RAM module (85) and thence used to control the system. The disc module is controlled by disc controller (87). Modifications to a program may readily be made when it is held in this RAM module, using the controls on the main control keyboard (70). Once a new program has been compiled and debugged, it can be transferred from this RAM onto a PROM using the PROM programmer module (86).

For the convenience of maintenance engineers, the maintenance module (82) is easily portable.

The complete system therefore consists of the System Processor Card (64), the Memory Card (66), the Keyboard/CRT control card (68), the Input/Output card (67) and sufficient Axis control cards (21) to drive the number of axes used on the controlled machine. In the preferred embodiment described the number of axis cards is 6, but there is accommodation provided in the cabinet, and in the multiplexing arrangements for ten axes to be served. In principle, the system may readily be extended to serve more than ten axes.

All the axis control cards are identical, even the preset adjustments appertaining to the properties of the different actuators in a system are implemented by software in the main controller, so, in the event of a malfunction in any axis module, a spare axis module can be fitted in its place and no adjustments are required before resuming operations.

TABLE 1: *AXIS CARD DATA BLOCK STRUCTURE*

	MOVE DESCRIPTION	COMMON MOVE PARAMETERS	CONTROL LOOP PARAMETERS
0		STATUS	
1		CONTROL	
2	LS TARGET	LS ALLOWED MAX ERR ERROR	FACILITIES ENABLE FLAGS
3	MS TARGET	MS ALLOWED MAX ERROR	MANTISSA GAIN (+DIR)
4	LS VELOCITY	ACCELERATION LIMIT	EXPONENT GAIN (+DIR)
5	MS VELOCITY	DECELERATION LIMIT	MANTISSA GAIN (−DIR)
6	LS INT DIST	MS VELOCITY LIMIT (LS = 0 IMPLIED)	EXPONENT GAIN (−DIR)
7	MS INT DIST	LS POS POSITION LIMIT	MANTISSA VELOCITY LOOP GAIN
8	LS MAX ERROR FOUND	MS POS POSITION LIMIT	EXPONENT VELOCITY LOOP GAIN
9	MS MAX ERROR FOUND (FIGURE OF MERIT)	LS NEG POSITION LIMIT	MANTISSA ACCELERATION LOOP GAIN
10	ERROR CODE	MS NEG POSITION LIMIT	EXPONENT ACCELERATION LOOP GAIN
11	SPARE	LS AXIS IN POSITION THRESHOLD (MS = 0 IMPLIED)	FUNDAMENTAL TIME UNIT
12	SPARE	LS AXIS STOPPED VELOCITY THRESHOLD (MS = 0 IMPLIED)	LS DITHER AMPLITUDE
13	SPARE	LS DATUM OFFSET	MS DITHER AMPLITUDE
14	SPARE	MS DATUM OFFSET	SPARE
15	SPARE	SPARE	SPARE
	BLOCK A	BLOCK B	BLOCK C

CLAIMS

1. A control system for multi-axis machine tool, welder, sprayer, robot or like mechanism in which the spatial position of the machine as a whole depends upon the contemporaneous positions of its several axes, wherein each axis is moved by an actuator and its movement is monitored by a transducer electrically connected to an individual control module including digital data processing means that repeatedly determines the distance through which the axis has moved, compares the position of the axis with an interim target position and supplies a control signal to the actuator to cause it to move in a required direction and velocity during the next time period until the axis has reached its final target position and a central controller that supplies target positions to the several control modules through a common data highway to bring about required axis movements.

2. A control system according to Claim 1, wherein the transducer means is arranged to supply an electrical signal to a directional logic circuit in the control module that produces clockwise and anticlockwise outputs which are supplied to individual counter circuits, and arithmetic means arranged to substract one count from another to produce an output denoting the magnitude and direction of the change in angular position signalled by said transducer means.

3. A control system as claimed in Claim 1 or 2, wherein each control module further includes means for calculating the velocity of the joint, the output of which is used to give a negative feedback component to the signal to the actuator to reduce oscillations thereof.

4. A control system as claimed in Claim 3, wherein each control module further includes means for calculating the acceleration of the joint, the output of which is used to give a negative feedback component to the signal to the actuator to reduce oscillations thereof.

5. A control system as claimed in any preceding claim, wherein each control module further includes means arranged to adjust the control signal to the actuator to compensate for sagging of the arm resulting from the weight of a workpiece that it carries.

6. A control system as claimed in any preceding claim, wherein each control module further includes means arranged to provide a correction to the control signal to the actuator to compensate for nonlinearity in the transfer function thereof.

7. A control system as claimed in any preceding claim, wherein each control module has means arranged to inject a "dither" component of cyclically varying amplitude into the signal supplied to the actuator at such a frequency and amplitude as to substitute dynamic friction of the respective axis for static friction.

8. A control system as claimed in any preceding claim, wherein the components of each control module are mounted on a respective individually removable printed circuit board.

9. A control system as claimed in any preceding claim, wherein the central controller is arranged to signal target positions to the several control modules at intervals, the several control modules are arranged to signal to the central controller at intervals how far the position of the respective axis differs from the target position after that interval and the central controller is arranged to supply updated control signals to the several control modules for the next interval.

10. A control system as claimed in claim 9, wherein the several control modules communicate with the central controller in time division multiplex.

11. A control system as claimed in any preceding claim, wherein the transducer is an optical encoder.

12. A control system for a multi-jointed arm or the like substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

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